INTERCOLLEGIATE ROCKET ENGINEERING COMPETITION TECHNICAL PAPER
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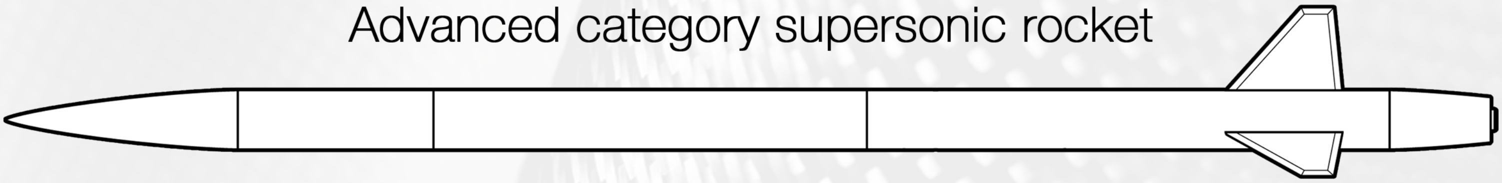
PERSÉUS

Advanced category supersonic rocket



Authors:
Vincent Bissonnette
Maxence Boutet
Mehregan Dor
Michael Fayad
Shahin Ghasemi
Pierre-Olivier Tardif
Jean-Gabriel Trudeau

Faculty advisor:
M. Pierre Laurendeau

Institution:
POLYTECHNIQUE MONTRÉAL
Québec, Canada

POLYTECHNIQUE MONTRÉAL

ORONOS
École Polytechnique de Montréal

8th Intercollegiate Rocket Engineering Competition, Green River, UT
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Abstract

The following report presents the team's final rocket and payload design as it will be used to compete in the 8th Intercollegiate Rocket Engineering Competition. First, a brief introduction gives an insight on the project's background and the team's objectives for current and future competitions. A description of the main preliminary design steps accomplished by the team to define all primary rocket characteristics is also given, followed by a more detailed view of avionics and recovery systems as well as design qualification tests. Finally, an overview of the final rocket features, specifications and expected performance is presented in a tabular format for easy reference.

Introduction and Background

Since its foundation in 2010, the *Oronos* Technical Society has striven to conceive, design, implement and operate high-power sounding rockets and participate in the annual ESRA IREC. With 30 active volunteering members, *Oronos* counts three different groups that deploy available financial and human resources to materialize the student-conceived rocket and concurrently ensure the rocket's compliance with specification requirements for a competitive performance on launch day.

The Aero group has the mandate to:

- Specify the necessary performances to meet the essential criteria at the IREC (dimensions, required thrust, weight, etc.) ;
- conceptually design the rocket, by considering innovative though safe designs for containment of payload and avionics, separation of sections and recovery of all rocket elements;
- apply in design and implement in execution fail-safe and safe-fail schemes in the operation of internal systems and in the succession of the various in-flight phases and processes (separation, recovery, etc.);
- decide on the configuration of the rocket section and compartmentalization, as well as on the disposition of internal systems, while keeping with proper weight distribution;
- conceive, design, construct and test all crucial internal mechanical systems prior to launch day;
- evaluate proper rocket dimensions for aerodynamic efficiency and attitude stability;
- evaluate proper materials for assuring structural integrity, while minimizing weight.

The avionics group fulfills the mandate of :

- integrating all necessary electronic hardware to of the internal computing unit and for the ground based station;
- conceiving and producing all required programming code
- conceiving and producing the scientific payload;
- operating the on-board computing unit and the ground based station;
- post-processing of gathered flight data;

The propulsion group has the mandate, as of now, of designing and producing a hybrid motor. This motor would, eventually, serve as a customizable motor for any *Oronos* produced rocket. Notably, a recent burn test of HTPB and liquid Nitrgoen Oxyde has been successfully carried out. However, the process of developing an engine has many phases, which will not be covered in the present report.

Rocket Design and Rationale

Major design decisions:

Primarily, the decision of using commercially available motors was taken at the very beginning of the 25,000 ft rocket project for participation in the Advanced Category, knowing that *Oronos* does not possess, at this moment, a fully developed homemade engine capable of being customized with proper thrust and total impulse to fulfill the advanced category competition requirements. During the preliminary design phase, a decision to exclude the development of a two-stage rocket was also taken, given the considerable added complexity in design and in launch and recovery event sequences.

Both these decisions greatly reduce the configuration possibilities, as most motors (H to L) can be excluded (not being able to lift the minimum weight with typical rocket design to reach 25k feet). In order to determine the proper combination of preliminary rocket structure dimensions and motor thrust/impulse, a 1D atmospheric simulator dedicated to initial design was developed and run to produce a list of suitable designs, if any exist. This simulator includes a CD model taken from windtunnel testing of a rocket of fineness greater than 13 as well as other CD data sources, from refs. [1,2,3,4], valid for Mach numbers of up to 3, taking into account the required drag coefficients, including those effective at transonic and supersonic regimes. Boundaries were imposed on the range of the varying parameters in order to respect other design requirements:

Varying parameters

Diameter*	5.51 in<D<2*D_eng
Total Mass**	>Eng_Mass + 10 lbs
Engine Model	> L class

*: It was decided early on in the design process that the rocket diameter would not be less than 5.51" for ergonomic reasons, as working by hand inside the rocket is strenuous at smaller diameters. The higher boundary on diameter size is needed to avoid aberrant designs (small motor diameter, large rocket diameter, meaning more total drag with high thrust but low impulse motor).

** : the desired simulation result is, in fact, the added mass budget for structure and systems excluding payload. Therefore, total mass is iteratively increased until a thrust to total weight ratio of 1 is obtained. The mass budget is the difference between total mass and the sum of payload and motor mass. Obviously, for considerations regarding successful ramp clearing phase, valid solutions with highest thrust to weight ratios and reasonable accelerations at lift-off were preferred.

Constant parameters :

Total Fineness Ratio*	20
Nose Cone Fineness Ratio**	5

* : based on previous *Oronos* protypes that have a suitable storage space for chutes and ejection/separation systems.

** Arbitrary.

The following results were gathered for the considered configuration limits :

Table 1 : Preliminary Design Simulations

Motor	Total Impulse (Ns)	Mass Budget (lb)	Altitude Max AGL (ft)	Load Max (g)	Drag Max (N)	Mach Max
N2900	17613	29	26778	13.0	660	1.44
N2900	17613	31	26099	12.5	640	1.40
N3301	19318	33	26785	12.5	660	1.44
N3301	19318	35	26138	12.1	639	1.41
N5800	20146	40	27963	20.7	761	1.54
N5800	20146	44	26644	19.6	715	1.46

The table illustrates that conservative altitudes are considered, as many sources of trajectory deviation from a 1D path might actually lower the achieved peak altitude, such as:

- weathercocking due to transverse winds at ramp clearing or during coast phase;
- deltas between ground level motor thrust curves and in flight thrust curves, due to differences between test conditions and flight conditions: heating of motor grain on ramp before launch by sunlight and due to changing ambient pressure during flight;
- deltas between simulation CD model and real CD evolution during flight, caused by difference between assumed skin roughness and resulting real roughness, which greatly influences the skin friction drag (major part of total drag in subsonic flight) and error associated with use of an empirical method.

Figure 1 illustrates the final simulation results with detailed design dimensions, weights and with the chosen motor. Conditions for simulation have been set to fully imitate launch day (June 21st) in Green River:

- Elevation of 4078 ft (pressure altitude and ground level reference for AGL altitude)
- Temperature 100 F

Structural design

Structural integrity and lightness are prime concerns in the rocket design phase. Initially, a supportive skin was chosen, allowing for the transfer of the forces throughout the rocket as well as holding the components segregated in different compartments for ease of assembly and take-off manipulations. Choice of material is critical, as it directly affects the weight and overall strength of the sounding rocket. Besides mechanical constraints, building limitations must also be taken into account when choosing a proper material, as the team's construction capabilities are limited, mainly having access to readily available hardware store tools. Ease of machinability is a crucial factor given the structure will be built with the use of hand tools.

Choice of composite material is justified by the real need to optimize the mass of the rocket without compromising its structural integrity. Hence, a carbon skin made by vacuum assisted infusion is chosen. This material and shaping process offers stiffness, lightness and a good surface texture, which is important for mating components (bulkheads, couplers, etc.).

Structural analysis

To determine the number of plies of carbon and their orientation, an analytical approach was used. The rocket will mainly be loaded axially by the applied engine thrust. Failure of the structure integrity would essentially come from a buckling process, the compression spreading through the carbon skin. The maximal compressive load was determined by simulations to be of 3098 N, after applying a safety factor of 1.5. This force was then used for computer assisted calculations on the longest (60 cm), less rigid fuselage section with no bulkheads to determine iteratively the ply sequence that will support the charge.

Table 2 : Carbon sleeve properties

Young's Modulus (GPa)	230
Yield Strength (MPa)	3000
Density (g/cm^3)	1.76
e (mm)	0.55
ε (%)	1.5

Using Kollar's composite laminate theory, it was found that using two layers of carbon sleeves of woven fibers $[45°/-45°]_s$ of 3K fiber would be largely sufficient. In fact, the first instability mode appears at 17 times the normal compressive load. Refer to Figure 2 for illustration. However, this analysis presumes a perfectly cylindrical fuselage tube, presenting no defects. Any defect will decrease this factor. Nevertheless, this factor is high enough to be confident in calculations. More so, the fuselage was modeled with simply supported ends, which adds to the conservatism: since the fuselage is glued to bulkheads, stiffness is added at the ends. These values were also confirmed by running FEM models of the fuselage part. A Tsai-Hill rupture criterion was also calculated during the iterative process, finding a low value of 0.002 (1.0 means rupture) for each ply, due to its symmetry. Comparison of the values obtained by manual calculations and FEM are presented in the following table:

Table 3: Results comparison

	Analytic	FEM
Deformation (mm) :	0.567	0.557
Buckling factor :	20.87	17.91
Tsai-Hill criterion	0.00207	0.00211

Engine bulkhead sizing

The motor mount was designed to distribute the load of the inertial force at launch through the skin. However, for a conservative approach, the bulkhead attachment was sized for taking all the force. The engine sits on the bulkhead on a small, 2” diameter area, which will result in a concentration of stress around the bolt attachment. This means not only calculating the resistance of the bulkhead itself by the applied force, but also the risk of de-bonds between it and the carbon skin. Refer to Figure 2 for illustration.

An epoxy cured at room temperature was used to bond the bulkheads to the skin. Theses bulkheads were made with high quality birch plywood, which is resistant, light, machinable and offers good bonding properties with epoxy.

Using shear bond properties for a standard epoxy (weakened at -60F to account for conservatism and altitude) and standard plywood mechanical properties, shear rupture and bulkhead failure were calculated using hand calculations and FEM.

Table 4: Epoxy de-bond results

Shear rupture :	
Force (N)	3090
Area (sq. mm)	5285
Shear (Mpa)	0.58
FS	21.89

Table 5: Plywood bulkhead FEM results

FEM bulkhead analysis :			
Von Mises at edges (Mpa)	3.77	FS	8.6
Von Mises at center (Mpa)	5.96	FS	5.7

A satisfactory safety margin for both epoxy de-bond and bulkhead failure was found for a thickness value of 1 inch (two ½ plies glues together) to account for the production defects and dry spots while gluing.

Systems Design, Analysis and Testing

Avionics

Parachutes Diagnostic System

The purpose of this system is to verify the successful deployment of the parachutes and send real-time data to the ground station. The parachutes diagnostic system monitors four events to confirm a proper parachute deployment.

1. It monitors whether the charges have exploded. This is done by a custom designed system in which a thin aluminum foil breaks when the detonation occurs;
2. The system measures the rise of pressure in parachute bay during the explosions;
3. The separation of the rocket is confirmed by the Hall-effect switches;
4. The rate of descent is measured to confirm that the rocket is consequently slowed down by the parachute.

The functionality of this system is assured by testing the following use cases.

- The ground station displays correctly the state of the charges when they remain intact.
- The ground station displays correctly the state of the charges when they explode.
- The circuit and the charges will be outside of the rocket in a testing environment. Charge explosions will be triggered by a manual emergency parachute deployment signal from the ground station and the ground station is expected to correctly display the change of state of the charges after their explosion.

Payload

The payload is intended to measure the effect of the transition from subsonic to supersonic regime. This is done by measuring the pressure distribution on the nosecone.

Nosecone Pressure Distribution

The effect of the transition between subsonic and supersonic will affect the pressure distribution over the rockets nose cone. There are 6 pressure differential sensors installed in the nose cone. Each one reads the difference of pressure between their respective port and the common static port. The normalised axial position of the sensors are:

$$X/l = [0.337\ 0.416\ 0.512\ 0.626\ 0.762\ 0.927]$$

Illustration 3 shows the predicted maximum static pressure on the nose cone. The positions of the sensors are also illustrated.

Circuits Design and Functionalities

Rocket Main module

This module contains two PIC32 microcontrollers for fast data processing and acquisition from the sensors. The sensors used are the following:

- Dual 3D accelerometers at two different scales (±16g, ±4g)
- Dual 3D rate gyroscopes at two different scales (±250deg/s, ±500deg/s)
- Single 3D magnetometer
- Single uniaxial 50g accelerometer
- Global positioning system (GPS)
- High accuracy altimeter
- Dynamic pressure sensor (Pitot tube)
- Battery level monitoring

All the hardware for the parachute diagnostic system is integrated on the main module.

The main module also has two data loggers for logging the data from the sensors while sending it in real-time to the ground station with a full duplex high power radio link. The main module will not log the sensors’ data that has already been logged in the secondary module. Secondary module sensors’ data will be sent to the main module with low power short range communication. Received data from the secondary module will be sent immediately to the ground station with the full duplex high power radio link.

The main module can also receive an emergency parachute deployment signal from the ground station. According to the signal information, the main module will either deploy the parachutes by triggering the upper 20A solid-state relay outputs or send the emergency parachute deployment signal to the secondary module that will trigger the bottom 20A solid-state relay outputs. Bottom and upper relay outputs will deploy the drogue parachute and the main parachute. In addition, a redundant power supply prevents a power failure of the main module.

The functionality of the main module will be assured by testing the following use cases:

- The ground station displays correctly the sensors data in a static environment.
- The gyroscope measures correct data according to a custom-made spinning table driven by a high precision stepper motor.
- The accelerometer detects 1g for the axis pointing to the ground in a static environment. Each of the three axes will be tested this way.
- The altimeter reads a similar altitude as a commercial altimeter.
- The magnetometer's calculated heading points to the same direction as a commercial compass in every circuit orientation.
- The calculated attitude in Euler angles is coherent with the rotations of the circuit.
- The GPS points to the correct rocket location.
- The data can be transmitted from the rocket to the ground station at a minimum distance of 15 kilometers. This range test will be made on ground in an environment with a minimal number of obstacles.

Rocket Secondary module

This module has the same circuit design as the main module for better interchangeability. The only difference is that the secondary module will not be linked to the ground station but will instead be linked to the main module for sending sensors' data to it and for receiving emergency parachute deployment signals from the main module.

The module's functionality will be assured by testing the same use cases as the main module except for the range test. Instead, the correctness of the short range transmission between the two modules inside of the rocket will be tested.

Rocket Parachute Deployment Module

This module was entirely designed by the avionics team and is the third iteration since the first homemade module. The module is also based on the PIC32 microcontroller and it contains the following sensors:

- 3D accelerometer
- 3D rate gyroscope
- 3D magnetometer
- High accuracy altimeter
- Optional global positioning system (GPS)

The module also logs the sensors' data and can trigger four 20A solid-sate relay outputs for parachute deployment.

Rocket Beacon Module

The beacon module has been designed as a replacement for the commercial FM radio beacon previously used. The advantage of this custom-made beacon is that it transmits the position coordinates with the help of its integrated GPS instead of sending a dummy radio signal. Also, a directional antenna can be used like in its previous version. The directional antenna can show the direction from which the signal is the strongest.

Ground Station Module

The primary function of the ground station is to receive rocket data and send it to the computer on which the ground station application is hosted. The ground station can also send a signal to manually trigger the deployment of the parachutes. The ground station also has a PIC32 microcontroller and two data loggers in case of a computer failure. In addition, a GPS is integrated to the ground station. This is very useful when the ground station is in movement for recovering the rocket. The GPS data helps approximating the rocket's distance from the ground station's position.

Drone On-Board Radio Relay Module

To prevent obstacles from blocking communication between the rocket and the ground station when the rocket is at low altitude or when it has landed, a fully automated hexacopter is used to ensure the relay of the telemetry. The integrated on-board system of the drone ensures the reception of the rocket's GPS position for fast recovery.

Avionic Bays Design

Every avionic bay was made from 3D-printed ABS thermoplastic parts. The upside of this fabrication technique is the possibility to design complex geometry and print them in a few hours. Every avionic component's position is defined in the 3D CAD assembly of the rocket and is easily printed. Refer to Figures 4 and 5 for illustration.

The avionics bays are designed to be "plug and play". On the launch site, all the modules are easily installed and connected. The bays can simply be inserted into the avionic compartment. Also, components outside of the avionic bays can easily be connected to them because of properly placed mating connectors.

Recovery system

The rocket's recovery system is characterized by a single ejection (single fuselage separation), with two distinct parachute deployments. When the rocket reaches its flight apogee, the avionics systems send an electrical discharge to two black powder charges located on top of the ejection compartment, causing a pressure build up in the parachutes' section and leading the two parts of the fuselage to separate. Shear pins are also used to prevent any premature opening of the chute section. The drogue chute, loose in the section, is then deployed by only mean of aerodynamic forces. This chute is directly connected to the upper part of the fuselage (i.e. the nose cone section) and is also linked to a wire cable and to the main parachute, which is in turn retained within the fuselage by a system detailed further.

Drogue chute deployment

In order to ensure the success of the fuselage separation and thus the deployment of the drogue chute at the apogee, black powder explosion tests were carried out under several controlled pressure conditions to assess the relationship between explosion efficiency and atmospheric pressure. Those tests, graphically detailed in Figure 6, led to the conclusion that black powder explosions are more efficient as the ambient pressure increases, which lead to the implementation of cork plugs in the design of the canisters used for black powder explosions. Those plugs' purpose is to keep the ambient pressure around the powder near that on the ground. As the explosions take place and the gas expands, the plugs are expelled out of the canisters, allowing the pressure to build up in the section. To ensure redundancy, the two explosions are triggered by two separate electric discharges.

Main chute deployment

As the fuselage separates, the drogue chute deploys, holding the fore and aft sections of the rocket with shock cords. The cord linked to the aft part is tied to the top of the main parachute, but a wire cable shortcuts it and is attached to two devices whose goal is to free the parachute at the desired height. The cable shortcut is intended to prevent the main chute from opening right after the drogue chute, and also serves as a retainer for the main chute. As shown in Figure 7, each device is composed of a box, having a longitudinal whole in which lies an ejection pin. The transversal slot's purpose is to allow the wire cable be held by the pin until the main parachute deployment is desired. A shear pin is also inserted on one side of the box and through the ejection pin in order to prevent the latter to move due to gravity or vibrations. On one end of the box, directly connected to the ejection pin hole, a hollow chamber filled with black powder is covered by a ¼" thick plate of G-10 plate, which is screwed tightly to the box. A rubber tape is also inserted between the plate and the box to ensure airtightness. An electrical resistance is inserted into the powder through two holes in the G-10 plate.

When the main parachute deployment is desired, an electric current is sent through both boxes' resistances, which triggers the explosion of the powder. The ejection pins are then expelled out of their boxes, freeing the wire cable and thus the parachute. The pull generated by the deployed drogue pulls the main chute out of the fuselage once the pins have been released. In order to guarantee the security of operators on the ground in the case of an accidental triggering, and also to ensure the rocket's structural integrity after the ejection, a pin catcher stands just ahead of each of the ejection boxes. The boxes are held steady by brackets that are screwed to the lower circular plate of the ejection module, which is removable from the rocket to ease operations. The module is in turn screwed to a bulkhead inside the rocket. As the drogue chute deploys and pulls on the main chute, the load path goes through the wire cable, then through the ejection pins and boxes, and finally through the brackets and the screws. Some experimental tests were therefore carried out with the proper load applied to the wire cable with the ejection boxes fastened by the screwed brackets to the bulkheads in order to make sure the pins are expelled even when loaded as the explosions occur. Furthermore, the test confirmed that the brackets could withstand that load. The applied load was 250 lbf on each pin, assuming that the lower part of the rocket, which weighs approximately 50 pounds, would undergo a 10g acceleration during the drogue chute deployment. The tests also led to the conclusion that 0.25 grams of black powder should be used in the pin release system to guarantee the success of the main chute release.

The redundancy of the main chute deployment as well as the recovery of the wire cable (in order to avoid its fall) is ensured by an appropriate disposition of the cable as schematized by Figure 8. As can be seen in Figure 8 a) the main chute is held under the wire cable until the pin release is achieved. As shown in Figure 8 b) c) and d), any of the three possible release cases allows the main chute to deploy, as the ring slides towards one end of the cable and the drogue chute begins to pull directly on the main parachute.

Final design summary

Airframe – Student built	
Fuselage external diameter	5.54 in
Fuselage internal diameter	5.518 in
Total airframe length	140 in
Primary materials	Fuselage skin : Carbon-epoxy composites Nosecone & tailcone : Fiberglass epoxy composites
Total loaded weight	72.8 lbs
Motor – Commercial	
Make and model	Cesaroni Pro98 6GXL N3301
Total impulse	19318 Ns
Average thrust	3301 N
Burn time	5.6 s
Recovery system – Student built	
Drogue diameter	48 in
Main parachute diameter	120 in
Drogue ejection method	Fully redundant dual black powder ejection canisters
Main ejection method	Dual pyrotechnically initiated release pins
Safety switches	2 external avionics deactivation keys
Payload and avionics - Student built, except one commercial altimeter for official altitude result	
Avionics bays	Dual bays with custom 3D printed avionics racks
Real-time data transmission	Full Duplex Radio-Link
Deployment Diagnostic System	Manual Emergency Overwrite for Chute Deployment
Fully Instrumented FCU	Altitude, 6 DOF Attitude (IRU, Magnetometer), Barometric, Airspeed, GPS
Drone Aided Relay System	Fast Recovery with Continuous Comm. with Rocket.
Expected performance	
Maximum altitude	26 138
Take-off thrust to weight ratio	12
Maximum acceleration	12.1 g (389 ft/s^2)
Maximum Mach	1.41
Time to apogee	40 s

References

1. Hart, Roger G.: “Flight Investigation at Mach Numbers from 0.8 to 1.5 to Determine the Effects of Nose Bluntness on the Total Drag of Two Fin -Stabilized Bodies of Revolution”, NACA Technical Note 3549, Langley Aeronautical Laboratory, Langley Field, Virginia, June 1953.

2. Waliskog, Harvey A. and Hart, Roger G.: “Investigation of the Drag of Blunt-Nosed Bodies of Revolution in Free Flight at Mach Numbers form 0.6 to 2.3”, NACA Research Memorandum L53D14a, Langley Aeronautical Laboratory, Langley Field, Virginia, June 1953.

3. Ellison, D. E.: “USAF Stability and Control Handbook (DATCOM),” AF Flight Dynamics Lab., AFFDL/FDCC, Wright-Patterson AFB, Ohio, August 1968.

4. McCormick, Barnes W.: “Aerodynamics, Aeronautics and Flight Mechanics”, pp. 315-331, John Wiley and Sons Inc., New York, 1979.

Figures

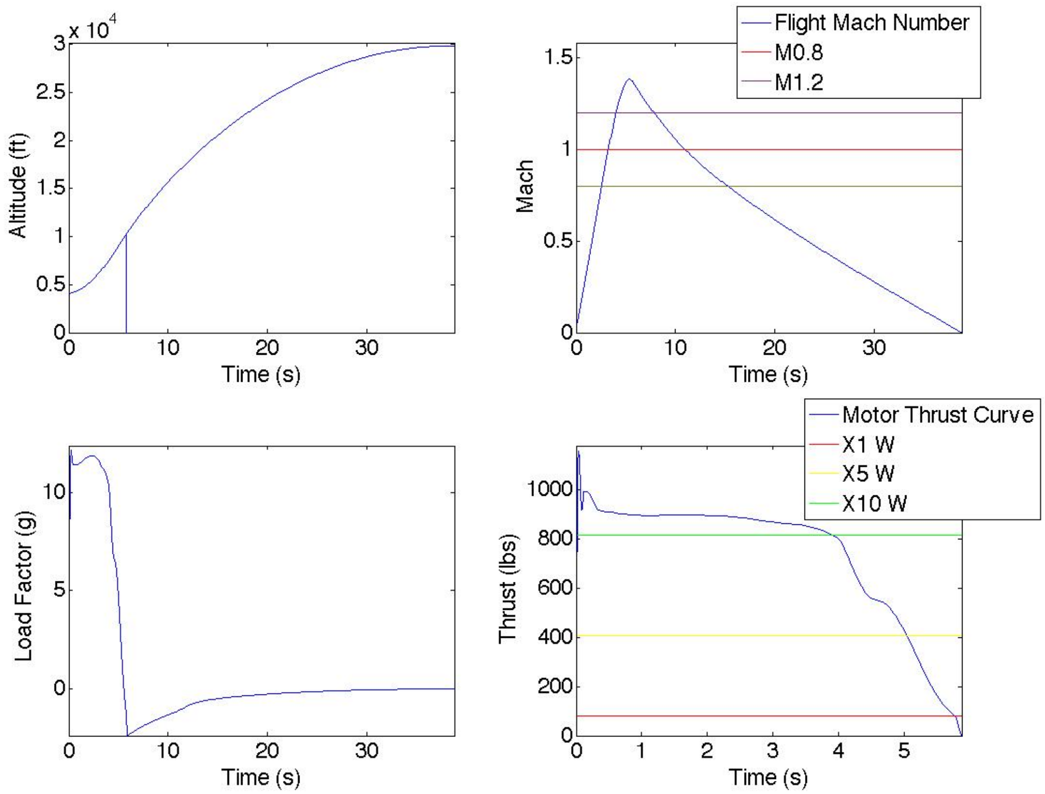

Figure 1 : 1D Simulation Results

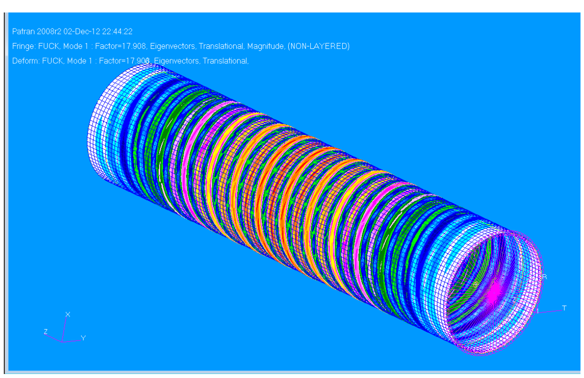

Figure 2 : First Buckling Mode Shape

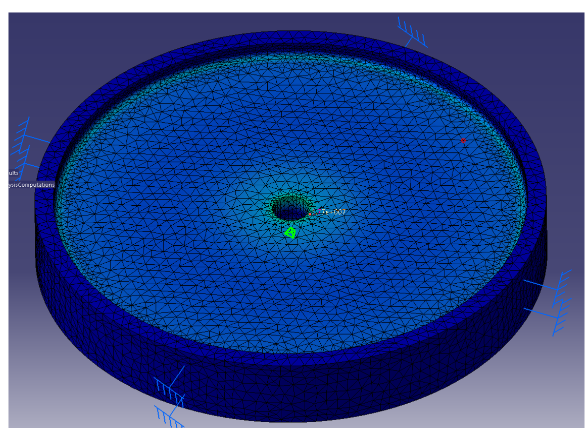

Figure 3: Bulkhead FEM

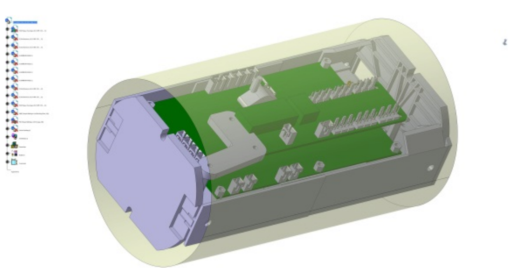

Figure 4 : Bottom Avionics Bay

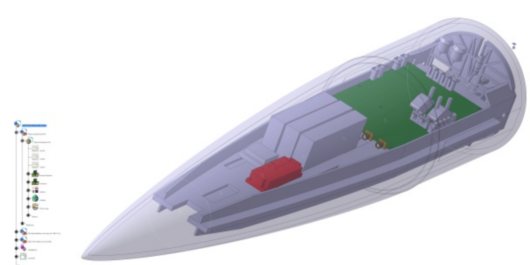

Figure 5 : Upper Avionics Bay

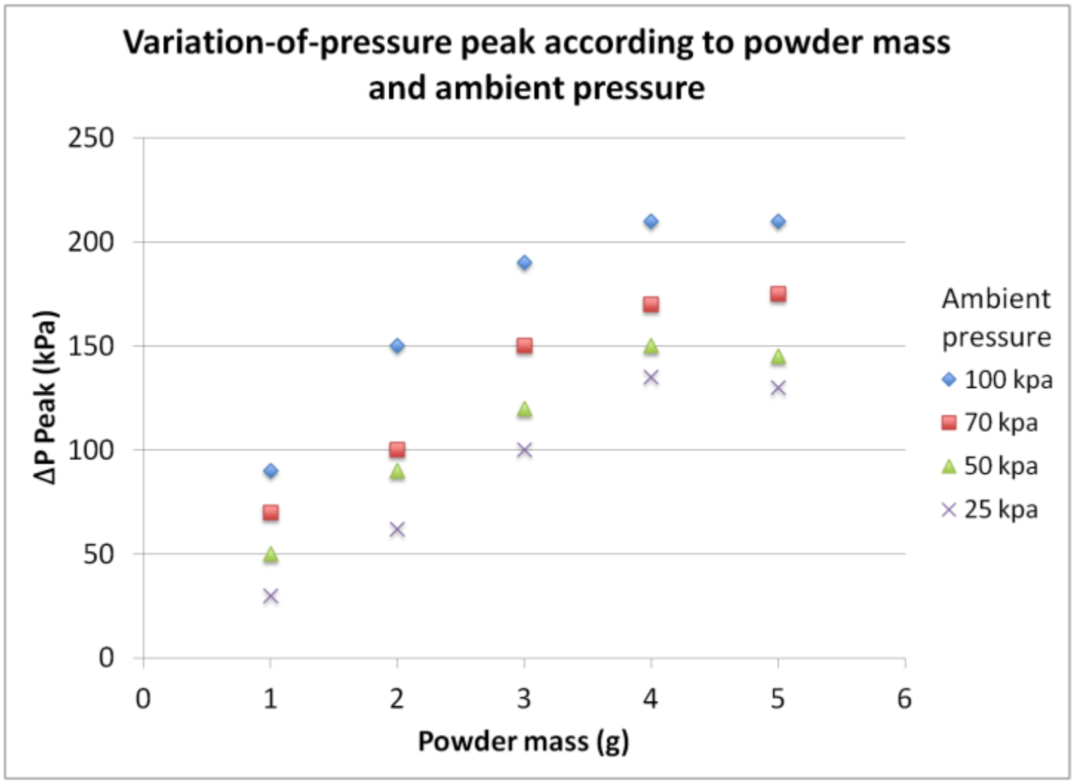

Figure 6 : Black Powder Test Results

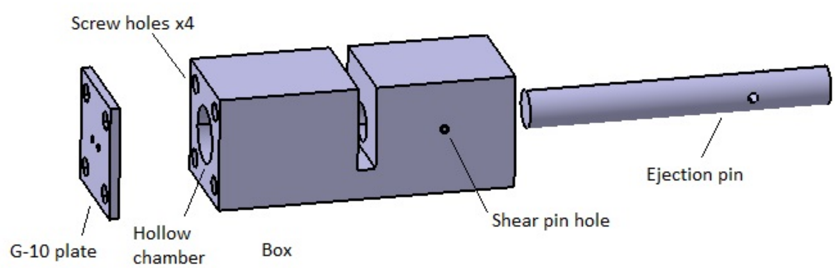

Figure 7 : Pin Release System

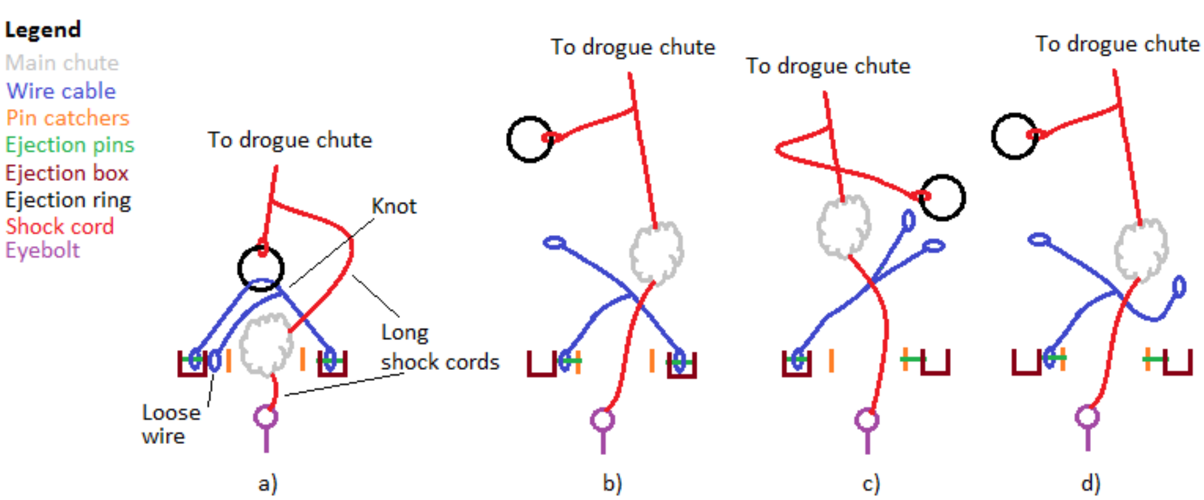

Figure 8 : Main Parachute Tether System